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DAMAGE ASSESSMENT IN A WALL STRUCTURE USING RESONANT FREQUENCIES AND OPERATING DEFLECTION SHAPES

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ABSTRACT

This paper describes the application of vibration modal analysis for detecting, monitoring and locating damage inside a wooden wall structure, by evaluating damage-sensitive parameters such as resonant frequencies and operating deflection shapes (ODS). Artificial damage was created in one of the walls of a specially constructed room. The wall was excited using an impact hammer and its frequency response was measured with a laser vibrometer. Damage-sensitive parameters were extracted from the frequency response and utilized for assessing damage, both qualitatively and quantitatively. Resonant frequency shifts and changes in ODS were used for detecting and monitoring the progression of damage, qualitatively. These methods make direct use of FRF data and mode shapes for damage assessment, which will help a lot in identifying damaged walls.

Key words: Resonant Frequency, Operating Deflection Shape, Structural Damage Assessment, Experimental Modal Analysis

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1. INTRODUCTION

Wooden homes are very commonly used in western countries and internal invisible damage in the load carrying wooden members is a very common problem. This internal damage is mostly caused by termites or in some cases ageing or due to some shock/impact loading occurred during any repair work/building work happened nearby. It is very important to assess this damage (identify and locate) in order to increase the life of homes. This paper is an attempt to develop a simple technique to do that. Vibration techniques have been used for assessing damage in structures [1-4], especially when the damage is located inside the structure and is not visually apparent. Other damage detection techniques such as ultrasonic

and x-ray scanning are believed to be cumbersome and expensive. Vibration techniques provide an inexpensive, fast and reliable method for assessing damage and have the potential for commercial application. Several vibration-related procedures have been suggested for detecting the existence and monitoring the progression of damage. One simple approach consists of comparing and monitoring resonant frequency shifts, which was also utilized in this paper as a preliminary study. Most vibration-related methods utilize the modal data at resonance as a parameter for damage assessment [5-7]. This requires a complete modal analysis to be performed for each successive damage stage and is time-consuming. A faster qualitative approach would be to compare the operating deflection shapes (ODS). In this approach, the modal curve-fitting process is needed only for the base line case. Visual interpretation of changes in the ODS of successive stages is used for damage detection.

The methods reported in this paper require a baseline/reference vibration response of the test structure to be acquired experimentally first. This baseline/reference simply provides a basis for comparison and need not be for the undamaged condition only. If successful, this technique can be applied to any kind of wall structure including concrete ones.

2. EXPERIMENTAL SETUP

To simulate realistic conditions, an enclosed room: 2.45 m (height) × 2.1 m (width) × 1.95 m (depth) with 2×4 wooden columns and gypsum plaster board, was used. This room was constructed inside a laboratory in the same manner as a typical wall in buildings and houses, where non-uniform column spacing and inconsistent usage of nails in walls are commonly encountered. The gypsum board is 1.2 cm thick, and each wooden column is 3.8 cm thick and 8.5 cm wide. The primary focus of this experiment is not the entire room but only one of the four walls, as shown in Fig. 1. The wall of interest, measuring approximately 2.45 m × 1.95 m, has a total of 6 vertical wooden columns (A to F). Nails were shot along the four corners of the room using a nail-gun. For the wall of interest, nails were also used to secure the base to the ground; one between columns B and C and the other between columns D and E.

Figure 2 shows the complete experimental setup for performing modal analysis. Data acquisition was performed using the Model 20-42 DSPT SigLab from Spectral Dynamics Corporation. It has good bandwidth up to 20 kHz range and a 3200-resolution line capability. The impact hammer was used to excite the structure and its vibration response picked up using a laser vibrometer. The force transducer used for input excitation is a PCB Piezotronic Model #086B01 Impulse Force Hammer with a force range of 0 to 100 lb_f. A metal tip is attached to the hammer-head for exciting a wider range of frequencies. For measuring velocity, a Polytec laser vibrometer was used. The system consists of a Model #OFV-350 optical head and a Model #OFV 2600 controller. The vibrometer was located approximately 60 cm from the target and its sensitivity set to 25 (mm/s)/V. The hammer was connected to channel 1 of SigLab through a signal amplifier unit and the vibrometer was connected directly to channel 4. The SigLab system was interfaced with a laptop computer via a PCMCIA card. Data was collected using a bandwidth of 0 to 200 Hz with a resolution, Δf of 0.5 Hz (800 blocks and 0% overlap). Force-exponential window was used to minimize leakage. Post-processing of the data like curve-fitting, animating mode shapes and ODS of the wall structure was performed using the ME' scope VES^{TM} vibro-acoustic software. Global curve fitting using Rational Fraction Polynomial (RFP) method was utilized for parameter extraction.

The wall was discretized into a total of 42 equidistant grid points, as shown in Fig. 1. All the points were located along the length of the wooden columns. Initial measurements were obtained at several locations with the laser and compared to determine the point where most resonant peaks appear (in the FRF). If the reference response (laser) is located at a nodal point

of one or several resonant modes, the transducer will pick up minimal response associated with that particular mode. As such, the laser beam from vibrometer was targeted at point #21 (an arbitrary point where response appeared to be acceptable) on the outside of the room. Trial runs indicated no difference in response, whether the room was impacted from inside or outside. For convenience, the wall was impacted from the outside. The procedure for performing modal analysis is elaborated by Avitable [8].

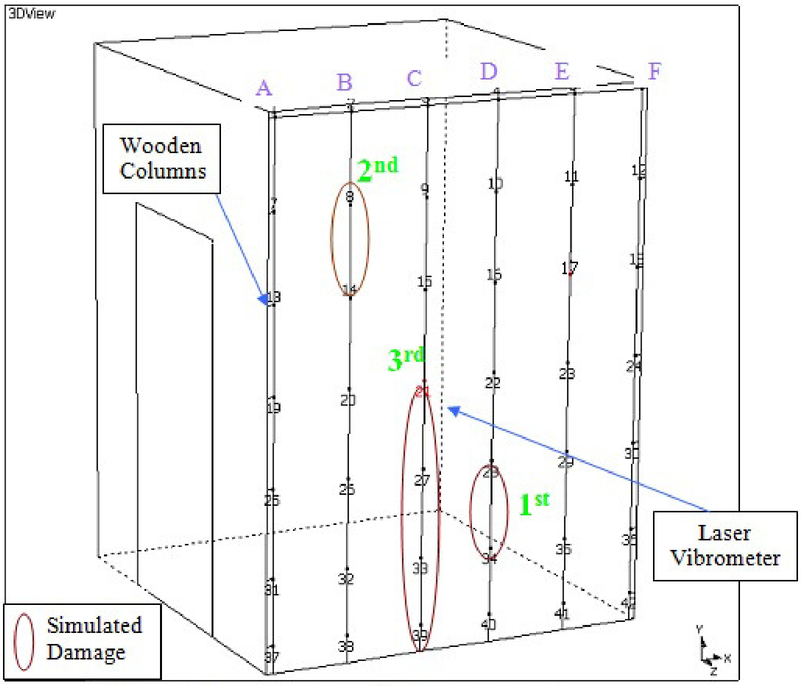


Figure 1 Model of the wall with simulated damage

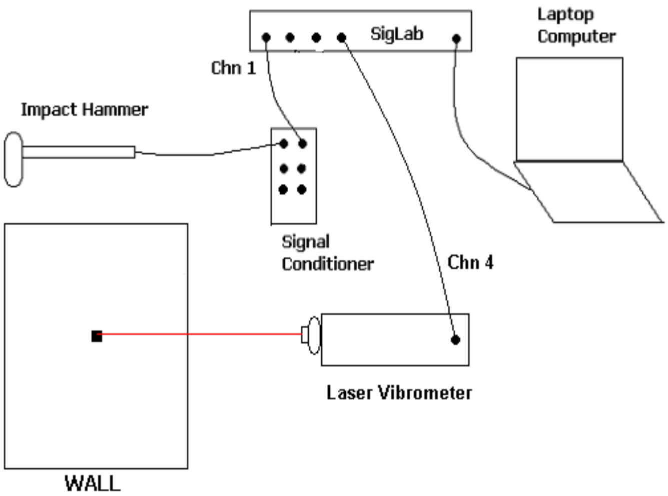


Figure 2 Experimental setup for acquiring FRF data

3. PROCEDURE

Once all calibration was completed, the impact hammer was used to tap each of the 42 grid points sequentially. The force and velocity responses were picked up by the hammer and vibrometer respectively, and processed into frequency response function (FRF) curves using the Fast Fourier Transform technique via SigLab. FRF is simply the ratio of the output

response i.e. velocity or acceleration of a structure due to input excitation force. The FRF data was then exported to ME'scopeVES^{TM} for post-processing. A baseline/reference FRF data set was obtained for the wall before artificial damage was introduced. The coherence of all points was checked to ensure that the quality of frequency measurement is acceptable. Coherence is a measure of how much output is caused by the input excitation and not by noise or other disturbances that could cause inaccuracies in the data. The coherence data also shows the linearity between two measurements. An acceptable measurement would have a coherence value of close to '1' over the frequency range of interest. It was observed that coherence data for points located at the boundary is poor, and therefore not used in the analysis. It is suspected that the low values of coherence at the boundary might result from non-linearity between the force (hammer) and velocity data.

Next, three separate progressive stages of damage were induced (holes simulating termite infestation) in the wooden columns (Fig. 1) using a hand-drill. It should be noted that damage simulation using hand drill causes loss in mass. The first-level damage was created along column-D between grid points #28 to #34. Second-level damage was induced along column-B between grid points #8 to #14. For the third-level, additional damage was created between grid points #21 to #39, from the base of column-C up to a height of approximately 110 cm. The level of damage created (or in other words, the amount of material removed) was approximately quantified to be 3% for the 1st level case, 6% cumulative damage for the 2nd level, and 14% cumulative damage for the 3rd level case. This percentage value is obtained by roughly estimating the portion (length) of damaged section over the total length of all the wooden columns inside the wall. All the 42 grid points were re-impacted for each successive level of damage and the response was acquired with the non-contact laser vibrometer. Testing was performed under ambient room conditions, with temperature and relative humidity between 22-24°C and 70-72%, respectively. These conditions were assumed to be constant throughout data acquisition process. Post analysis was performed using the ME'scopeVES^{TM} vibro-acoustic software [9], to extract damage-sensitive parameters for detecting and locating the damage region. The methodology and results obtained using both the qualitative and quantitative techniques are described in the following sections.

4. RESULTS AND DISCUSSION

4.1. Frequency Shifts

As mentioned, post processing and data extraction from the FRFs was performed using ME'scopeVES^{TM}. Narrowband global curve fitting using Rational Fraction Polynomial (RFP) method was used to obtain the dynamic properties i.e. resonant frequencies, damping and mode shapes. The first twelve modal frequencies obtained using the laser vibrometer are tabulated in Table 1. Resonant modal frequencies are represented by peaks in the FRF curve as shown in Fig. 3, for the baseline case at driving point. Driving point is the point where the impact location and reference response (laser) are coincident. Each peak represents one mode of vibration.

As mentioned, a total of three cumulative levels of damage were induced. It is expected that the resonant frequencies drop as damage is induced, since frequency is proportional to stiffness, as shown by the generalized expression below [10]:

$$\omega_n = \frac{\int_0^L k(\frac{d^2 w(x)}{dx^2})^2 dx}{\int_0^L \rho A(w(x))^2 dx} \tag{1}$$

where ω_n, k, ρ, L and A are the natural frequency, stiffness, density, dimension, and cross section area of the structure respectively, and w(x) is the mode shape function. Fig. 4 shows a plot of the baseline, 2nd level and 3rd level FRF (at driving point) superimposed together. It was observed that the frequencies drop as successive damage was created.

Presence of damage lowers the structural stiffness, thus causing a reduction in resonant frequencies. However, some types of damage like drilling as in this case, also cause mass reduction. Although mass plays a role, it is expected that the effect of damage on stiffness is generally greater than the mass effect [11]. In cases where mass is reduced significantly without much change to stiffness, the structure's flexural resonant frequencies may show an increase after damage induction. This is when the mass effect is more dominant than the stiffness effect. One example is when damage (by drilling) is formed at the neutral axis of the 2×4 wooden beam, which has been demonstrated by the author [12,13]. However, for most cases where structural damage is significant, the presence and extent of damage may be monitored through frequency reduction.

The results in Table 1 show that frequency reduction is dependent on two attributes; magnitude and location of damage. Comparison of frequencies between the baseline and 1st level damage indicates a slight drop only for some of the frequencies. An increase in frequencies for some other modes could be attributed to mass and damping effects being more dominant [7], provided other parameters like temperature and moisture are maintained constant. Recall that the 1st and 2nd level damage (located between grid points #28 to #34 and #8 to #14, respectively), are relatively smaller in size compared to the 3rd level. The amount of damage is almost identical for these two cases, and an inexperienced investigator would expect that the percentage of decrease in frequency would be equal from 1st case to 2nd case, as it is from baseline to 1st case (with other parameters assumed unchanged). It is observed, however, that for most of the modes the magnitude of decrease in frequencies from baseline to 1st level case is more than the decrease from 1st level to 2nd level case. This means that the effect of the 1st level damage on modal frequencies is greater than 2nd level case, even though the amount of damage created for both cases is almost identical. Hence, there is another parameter that affects frequency shifts, besides the amount of damage itself, which would be the location of the damage region.

Table 1 Damped Modal Frequency, ω_d (Hz), for Various Levels of Damage

Mode #	**Baseline Data**	**1st Level Damage**	**2nd Level Damage**	**3rd Level Damage**
1	17.92	16.04	16.03	15.13
2	21.63	21.47	21.67	20.83
3	28.68	28.85	27.81	26.66
4	31.14	31.53	32.03	31.47
5	39.50	39.94	39.38	36.79
6	47.09	45.94	45.88	45.34
7	55.98	54.52	54.53	53.14
8	65.94	62.38	*	*
9	71.03	*	66.99	65.52
10	78.60	73.40	73.10	72.81
11	84.18	81.59	82.28	82.97
12	95.79	95.05	93.91	-

* Missing modes

Figure 3 FRF curve for the Baseline case at driving point

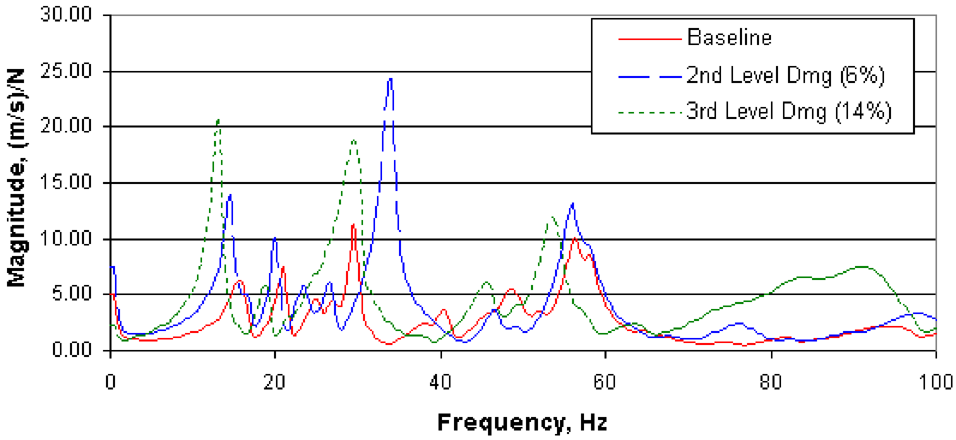


Figure 4 Superimposed FRF for Baseline and Damaged Case

The dynamic response of the side wall simulates a fixed-pinned configuration and with damage located at a region of high strain energy density i.e. at the fixed end, the effect on the dynamic properties would be greater compared to damage located at a lower strain energy region. 1st level damage is located at the fixed end while the 2nd level damage is at the upper-pinned end having lower strain energy. The effect of location and boundary conditions on the resonant frequencies of a complex structure (such as this wooden wall), is not as apparent as it is for a simple 2×4 wooden beam [11, 12]. Also, the extent of damage created for the first two cases may not be sufficient for dramatically affecting the resonant frequencies.

The modal frequencies for the 3rd damage case show the greatest percentage reduction (Table 1). This is because the amount of damage created between grid points #21 to #39, is approximately three times the amount created for each of the first two damage cases. This reinforces the concept that more damage would result in a greater reduction in resonant frequencies. The observations made here indicates that the existence of damage does influence the modal frequency i.e. modal frequencies decrease due to the presence of damage, and therefore can be used as a parameter for detecting and monitoring the progression of damage. The magnitude of this ‘influence’ or in other words, the amount of decrease in frequencies (for similar sized damage), was also observed to be affected by the damage location and boundary condition. The highlight of this approach is to use the relative drop in modal frequencies to detect the presence and monitor the progression of damage. The setback to this approach is that it is more sensitive to major structural damage, and may not be successful at detecting minor damage. Also, it should be noted that this study is valid if temperature and humidity is maintained constant and is assumed to have no contribution. A study of the affect of these environmental factors is currently under investigation.

4.2. Comparison of ODS for damage detection

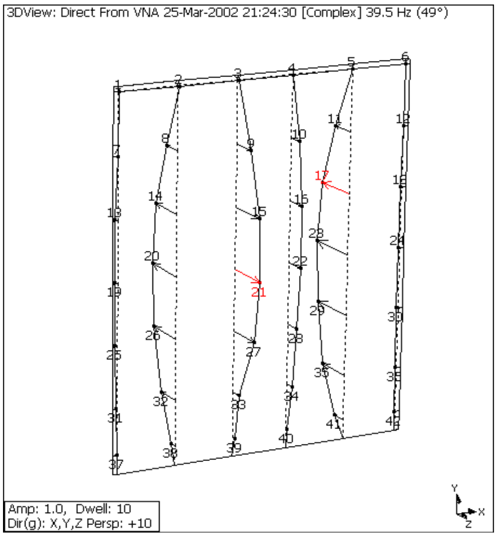
Another qualitative approach for assessing structural damage is a comparison of the operating deflection shapes (ODS), before and after damage. This approach however, is useful for detecting the presence of damage and monitoring its progression if the damage is sufficiently large. ODS is the deflection or deformation of the structure at a given frequency. It should not be confused with resonant mode shapes, which are an inherent property of the structure and unique for each mode of vibration, whereas ODS is dependent upon the loading condition. Mode shapes are dimensionless quantities whereas ODS can be specified in terms of displacement, velocity and acceleration. The ODS consists of all the modes of vibration interacting together to give the actual vibration (deformation) behaviour of the structure at a particular frequency of interest. When the excitation frequency coincides with the natural frequency, only one dominant mode will characterize the deformation pattern, with the effects of other modes attenuated and the unique deformation pattern of a resonant mode will appear. In other words, the mode shape can be considered as a special case ODS at resonance.

If a machine operating at a particular frequency is damaged, one would expect the ODS before and after damage to be different. This is similar for structural damage. The actual deformation at a selected frequency would change once damage is present. This is the basis for utilizing ODS for detecting and monitoring damage, inside the wooden wall. The advantage of this approach is that complete modal analysis, which includes the mode shape curve-fitting process, is not required for each successive damage case. The deformation pattern at any frequency can be used for comparison. For the purpose of this investigation, the undamaged (baseline) resonant frequencies are taken as the reference frequency, since the resonant frequencies have already been acquired. The deformation patterns for each successive level of damage were obtained and compared with each of the baseline reference frequency mode shapes.

In comparing ODS patterns, the relative change in the ODS pattern between the damaged case and the undamaged baseline case are monitored. As more damage is introduced into the structure, the ODS pattern will differ greater, since it will be affected by the contribution of other modes. The degree of influence of other modes on the ODS pattern is dependent upon the extent of damage with frequency reducing as damage increases.

The ODS patterns can easily be generated in ME'scopeVES^{TM}. This is done by drawing the structure (with grid points) and then assigning the FRFs to the measurement grid points. ME'scopeVES^{TM} can then animate the ODS at any frequency. Figs. 5 and 6 show the freeze-frame ODS for baseline, 1st level, 2nd level and 3rd level damage for Modes 5 and 9, respectively. The ODS pattern changes as more damage is induced in the structure. The effect of 3rd level damage on Mode 9 (Fig. 6) is large enough that it changes the deformation pattern quite a bit. It can be observed that the ODS of the 3rd level damage is different from baseline ODS. This mode is ideal for monitoring the progress of damage, since the change in ODS between each successive level of damage is obvious. Not all modes, however, can be used for monitoring, since the presence of damage does not affect all modes equally. A basis for selecting which modes are affected by damage has been suggested by Khoo [13].

This qualitative approach can be used for detecting the presence of damage provided the damage is significant. ODS comparisons for minute damage that has little effect on the deformation pattern is not recommended. Another, disadvantage is that the ODS patterns can be misinterpreted by different investigators, especially for small damage. Although utilization of ODS may not be the best approach for damage assessment, ODS patterns are nonetheless a valuable tool in machine diagnostic and design [14].



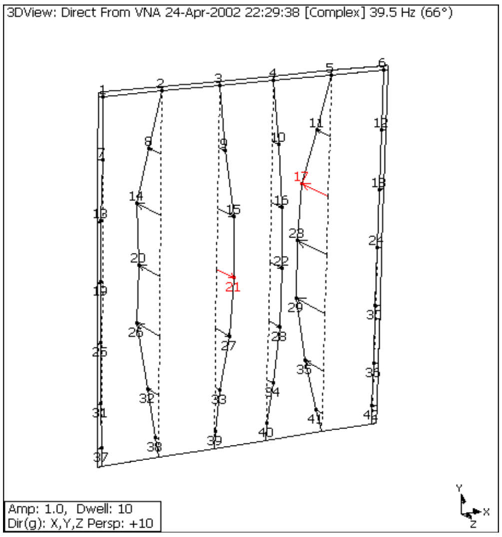
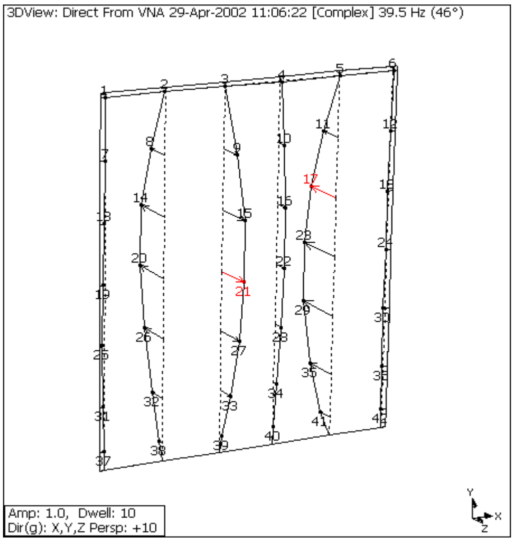


Fig 5(a): Baseline mode shape @ 39.5 Hz (Mode 5) **Fig 5(b):** ODS @ 39.5 Hz (Mode 5) 1st Level Damage



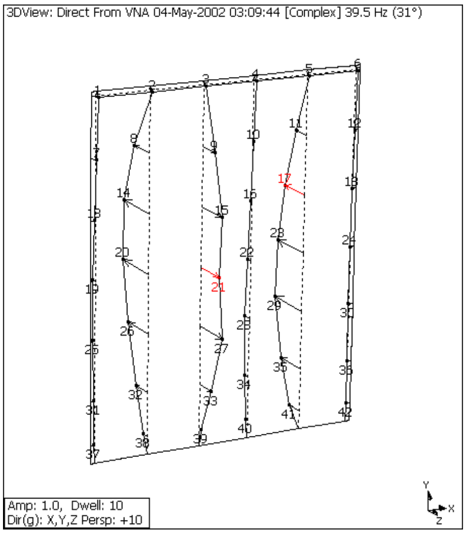


Fig 5(c): ODS @ 39.5 Hz (Mode 5) 2nd Level Damage **Fig 5(d):** ODS @ 39.5 Hz (Mode 5) 3rd Level Damage

Figure 5 ODS comparison of Mode 5 @ 39.5 Hz

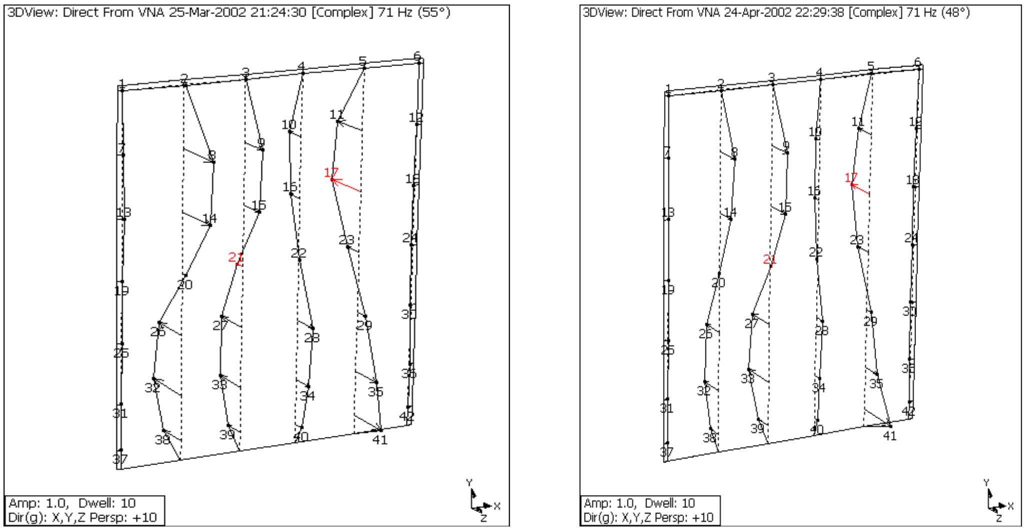


Fig 6(a): Baseline mode shape @ 71 Hz (Mode 9) **Fig 6(b):** ODS @ 71 Hz (Mode 9) 1st Level Damage

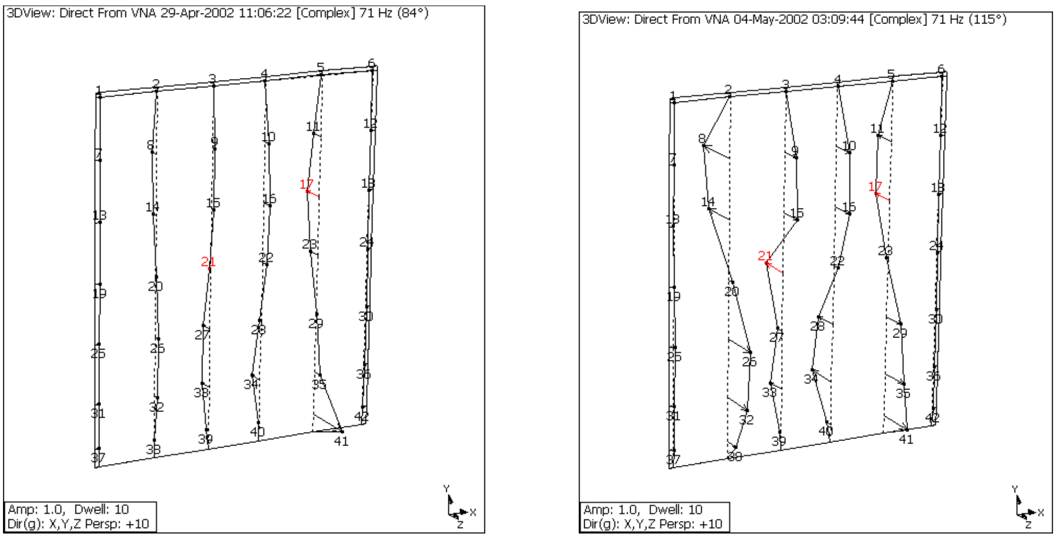


Fig 6(c): ODS @ 71 Hz (Mode 9) 2nd Level Damage **Fig 6(d):** ODS @ 71 Hz (Mode 9) 3rd Level Damag

Figure 6 ODS comparison of Mode 9 @ 71 Hz

5. CONCLUSIONS

Two qualitative vibration based approaches for assessing structural damage have been described in this paper. An experimental investigation using an actual wooden wall with plasterboard was performed to demonstrate the feasibility of these approaches. Data acquisition was performed using the conventional 'roving hammer - fixed transducer' impact vibration testing. In the qualitative approach, the presence of damage was detected and its progress monitored by either tracking resonant frequency shifts or visually identifying changes in the Operating Deflection Shapes (ODS). The presence of damage causes a decrease in structural stiffness, characterized by a reduction in the resonant frequencies. The deformation pattern of the undamaged and damaged structure will be different and therefore can be used for detecting whether additional damage exists or progresses in the structure. For locating the damage however, new quantitative methods need to be developed which can précised locate the damage and easier and faster to use.

For commercial or large-scale applications, data acquisition by impact testing is time consuming. When dealing with complex structures, finer discretization or more data points are needed for improved accuracy and precision in locating damage. It is believed that more sophisticated instruments like the Scanning Laser Doppler Vibrometer (SLDV) can be implemented for faster and finer data acquisition. A fully automated damage assessment tool that utilizes both SLDV and the broadband FRF quantitative approaches presented in this paper show potential for commercial or large-scale applications. Investigations are currently ongoing for refining this technique using such sophisticated instrumentation.

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